Cogent Engineering

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/oaen20

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To cite this article: Theophilus Aanuoluwa Adagunodo, Oyelowo Gabriel Bayowa, Ayobami Ismaila Ojoawo, Olusegun Oladotun Adewoyin, Patrick Omoregie Isibor, Emmanuel Ayibaifie Jephthah & Nicholas Oliseloke Anie (2022) Investigation of foundation bed's characteristics and environmental safety assessment in some parts of Bayelsa State, south–south Nigeria, Cogent Engineering, 9:1, 2119533, DOI: 10.1080/23311916.2022.2119533

To link to this article: https://doi.org/10.1080/23311916.2022.2119533

Published online: 13 Sep 2022.

Adagunodo et al., *Cogent Engineering* (2022), 9: 2119533
https://doi.org/10.1080/23311916.2022.2119533

cogent engineering

CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

Investigation of foundation bed's characteristics and environmental safety assessment in some parts of Bayelsa State, south–south Nigeria

Theophilus Aanuoluwa Adagunodo[1*], Oyelowo Gabriel Bayowa[2], Ayobami Ismaila Ojoawo[3], Olusegun Oladotun Adewoyin[1], Patrick Omoregie Isibor[4], Emmanuel Ayibaifie Jephthah[1] and Nicholas Oliseloke Anie[5]

Received: 09 April 2022
Accepted: 28 August 2022

*Corresponding author: Theophilus Aanuoluwa Adagunodo, Department of Physics, Covenant University, Ota, Ogun State P.M.B. 1023, Nigeria
E-mail: taadagunodo@yahoo.com

Reviewing editor:
Sanjay Kumar Shukla, School of Engineering, Edith Cowan University, Australia

Additional information is available at the end of the article

Abstract: The application of appropriate geophysical survey is very pertinent in planning for a successful development of civil engineering structures. In this study, an uphole seismic refraction survey and borehole logs were used to determine the foundation bed's characteristics for civil engineering development, while a portable gamma spectrometer was used to assess the environmental safety worthiness in some parts of Bayelsa State, Nigeria. The seismic refraction revealed a two-layer model, composing of an unconsolidated layer and a consolidated layer. The overburden thickness of the unconsolidated stratum varied from 2.2 to 7.5 m. The borehole logs showed alternating sequence of clay and sand up to a depth of 60 m. The radiometric survey revealed that thorium and the average radioactivity ratios of U/K, Th/K and U/Th are above the global standards by factors of 1.4, 6.4, 11.0 and 2.3 in sequence. Though the overburden in the study area is thin, it is advisable to excavate some aerated soil materials within the unconsolidated layer to minimize the effects of clay on the structure's foundation. Furthermore, periodic environmental safety monitoring and assessment is recommended in the study area.

ABOUT THE AUTHOR

Theophilus Aanuoluwa Adagunodo

Theophilus Aanuoluwa Adagunodo is the current Postgraduate Coordinator at the Department of Physics, Covenant University, Ota, Nigeria. He has contributed to several publications both as a lead-author and a co-author. He has served as Managing Editor, Associate Editor, Guest Editor and Reviewer to many high-profile journals. As part of the reward for diligence in his career, he has been listed twice as one of the Chancellor's Exceptional Researchers at Covenant University in the 2018/2019 and 2019/2020 academic sessions. His research interests include Environmental Geophysics, Engineering Geophysics, Groundwater Exploration, Structural Analysis, Seismology, Seal Integrity/Fault Seal Analysis, Reservoir Characterization, Mining, Geodesy, Medieval Climate Anomaly, and Radiometrics. He is a member of the Nigerian Institute of Physics.

PUBLIC INTEREST STATEMENT

This study integrates an uphole seismic refraction and in-situ radiometric methods to determine the foundation bed characteristics and environmental safety of inhabitants in part of Bayelsa state against radiation exposure for an enhanced subsurface integrity check. The overburden in the study area is composed of two-layered earth model heterogenous materials with varying depths. Despite the thin overburden, it is advisable to excavate the weathered layer in order to minimize the effect of clay on the structure's foundations. The radiometric geospatial maps revealed that thorium and uranium contents are higher than the global limits. The risk assessment revealed that the annual gonadal equivalent dose is slightly higher than the global average. The risk being exposed to in the study area could lead to gradual depletion in the amount of the total red blood cells produced by the bone marrow of the inhabitants.

Subjects: Earth Sciences; Natural Hazards & Risk; Geology - Earth Sciences; Engineering Geology; Geophysics; Environment& Health; Environment & the City; Applied Physics; Environmental Physics

Keywords: engineering geophysics; environmental safety assessment; foundation bed's integrity; radiometric survey; uphole seismic refraction

1. Introduction

The rate at which structural failures occur recently in Nigeria is terrifying (Akintorinwa & Adelusi, 2009; Awoyera et al., 2021; Ede, 2010; Hammed et al., 2017). Its occurrence has led to the loss of lives and invaluable properties in Nigeria and some other developing countries (Dimuna, 2010). Some of the contributing factors to incessant structural failures in these developing nations include inadequate experience about the nature of the near-surface structures, usage of substandard materials for constructions, extraordinary loads, unprofessional/bad designs, foundation failure and natural disasters (such as earthquake, fire, flood, among others) (Dimuna, 2010; Oyeyemi et al., 2020). Reports had shown that most of the failures in Nigeria (when classified in terms of geological settings) occurred in sedimentary environments (Awoyera et al., 2021; Ede, 2010; Odeyemi et al., 2019; Okagbue et al., 2018; Oseghale et al., 2015). To properly understand the nature of the near-surface structures before the construction of any civil engineering structure, it is imperative to carry out a geophysical survey at the subsurface to determine its competence or suitability (Hammed et al., 2018).

The two major subsurface investigations before construction activities are conceptual and detailed subsurface investigations (Hammed et al., 2017). The former entails checking some surficial features (such as sinkholes, cavities, old fill, or slopes) before construction activities. However, the latter entails thorough checking of near-surface features, which could be achieved by conducting a geophysical survey and geotechnical test in such an environment (Mayne et al., 2001). Geotechnical investigations have been proved to be acceptable in that information such as soil structures, soil compositions, lithologic profiles and the soil bearing capacity could be determined by using geotechnical tests (Oyeyemi et al., 2020). However, these methods of investigation are not without their shortcomings in that they are cumbersome, very invasive and non-environmental friendly (Mohd et al., 2012). In recent times, geophysical techniques have been used to investigate the condition of the subsurface for construction purposes (Adegbola et al., 2012; Azahar et al., 2018; Obare et al., 2020; Rasul et al., 2015; Soupios et al., 2007). These methods have proven to be very reliable, non-destructive, environmentally friendly and less expensive. This approach can also give information on the lateral variation in the geologic condition of the subsurface with depth (Adewoyin et al., 2021). Bacic et al. (2020) opined that the adoption of a geotechnical test is limited by the cost and time required to carry out a significant subsurface investigation in comparison to a geophysical survey. Furthermore, the information provided by vertically drilled boreholes for the geotechnical survey is solely restricted to the point of investigation as the sub-vertical features that are parallel to the axes of drilled boreholes are undiscovered (Balia & Manca, 2019). In contrast, geophysical techniques have revealed the properties of the subsurface rock mass in non-invasive and non-devastating ways (Bacic et al., 2020). George et al. (2015) demonstrated that aquifer's hydraulic parameters could be estimated from geophysical methods. Also, the effectiveness of the seismic refraction method for geotechnical investigations had been demonstrated by some authors both in soft terrain and in hard terrain (Aka et al., 2018; Bacic et al., 2020; Bawuah et al., 2018). Due to these qualities, geophysical techniques possess a favourable information-to-cost ratio (Adewoyin et al., 2019; Balia & Manca, 2019). However, geophysical surveys are not to replace geotechnical investigations, when the latter is not available geophysical methods could be effectively used for subsurface characterisation (Tezcan et al., 2009).

Several geophysical methods (such as electrical resistivity, seismic refraction, magnetics, gravity and electromagnetics) have been adopted for geostructural surveys (Adegbola et al., 2012;

Adewoyin et al., 2017; Aka et al., 2018; Anderson et al., 2008; Azahar et al., 2018; Bawuah et al., 2018; Hammed et al., 2017; Liu, 2007; Mantlik et al., 2009; McGinnis et al., 2011; O.G. Bayowa et al., 2019a; Obare et al., 2020; Oladejo et al., 2020, 2019; Rasul et al., 2015; Soupios et al., 2007; Yusuf et al., 2015). Electrical resistivity and seismic refraction are the most common approaches used for site characterisation prior to excavation and construction activities (Adiat, 2019; Alabi et al., 2018; Bryson, 2005; Drake, 1962; Kiernan et al., 2021; Lech et al., 2020; Oladunjoye et al., 2017; K. Rezaei et al., 2013; Rucker et al., 2010; Sudha et al., 2009). Meanwhile, seismic surveys have been reported to be advantageous in near-surface investigations, due to their ability to provide a fast subsurface model that aids site characterisation (Azahar et al., 2018; Bawuah et al., 2018; Lucas et al., 2017; Tezcan et al., 2009). In seismic refraction, the primary waves that are refracted to the surface at the boundaries exhibit different velocities, which are analysed by Snell's Law to infer some geomechanical parameters.

Recently in Nigeria, interest has been shifted towards the adoption of travel times of first breaks in an uphole refracted seismic energy to determine the weathered layer's parameters (velocity and thickness) of a surface seismic survey (Adegbola et al., 2012; Adeoti et al., 2013; Ofomola, 2011). The velocity of the weathered layer can be obtained from the seismic data, shallow uphole or downhole refraction surveys (Alaminiokuma & Amonieah, 2012; Enikanselu, 2008; Kim et al., 2004; Kolawole et al., 2012). The weathered layer is basically characterised by low seismic wave transmissions and low shot frequencies because this layer can absorb high frequencies. A key advantage of conducting an uphole refraction survey is to obtain a direct value for a travel time in a low-velocity layer (LVL) and the strata beneath it, which is usually unweathered and consolidated (Woodward & Menges, 1991). Below the unconsolidated layer, holes are being drilled and geophones are set at varying known depths within these holes to overcome the problem of weathering layer absorption (of seismic waves) while embarking on a seismic refraction survey (Ogagarue, 2007).

In environmental sciences, the safety of man from environmental hazards is of great concern. A polluted environment is harmful to its inhabitants. An environment could be polluted either from natural or artificial sources (Akpan et al., 2016). One of the methods by which the safety of an environment could be assessed is by conducting a radiometric survey to ensure that the inhabitants of such an environment are not ignorantly exposed to excessive background radiation (Adagunodo et al., 2021). Natural radioactivity is present in rocks, water, soil, other abiotic components as well as biotic entities present in an environment. The levels of radiation in rocks and soil depend on the composition of series of decayed radioactive elements (such as ^{238}U, ^{232}Th and ^{40}K) in the parent rock (Amadi et al., 2012). Naturally, some locations are composed of elevated concentrations of certain radioelement than others. If such anomalous zones are not detected on time, it could lead to serious health issues (one triggered by gamma-radiation) among the dwellers (Omeje et al., 2019). Some of the health challenges that are associated with over-exposure to radioactive elements include series of lung diseases, different types of bone diseases and cancers of various types (Usikalu, Oderinde, Adagunodo, Akinpelu et al., 2018a). Leukaemia, hepatic, kidney diseases, liver diseases and some malfunctioning of internal organs had been linked to over-exposure to thorium, uranium and potassium (Ramasamy et al., 2011).

The natural occurrence of radioisotopes in an environment is a function of the geochemical processes that have tenderly reformed the crustal materials from the crust–mantle interactions. These radioactive components within the crustal rocks enable radiometric prospecting for lithological mapping a successful quest (Adabanija et al., 2020; Frattini et al., 2006). In geosciences, ^{238}U, ^{232}Th and ^{40}K are the major important radioelements in mineral exploration and geologic mapping (Amadi et al., 2012). These three radioelements had been used to determine the potential of some certain rocks or locations to generate high radiogenic heat that could be useful for the Nigeria Atomic Energy Commission (Adabanija et al., 2020; Chad-umoren & Osegbowa, 2011; Ogunsanwo et al., 2021). Furthermore, only uranium, thorium and potassium radioisotopes are required for the prediction of inhabitant's safety from gamma radiation's exposure in an environment (IAEA

(International Atomic Energy Agency), 2003). Although gamma-ray spectrometry has greatly been used for uranium exploration, the advent of the spectrometer has made its scope and uses be noticed in environmental studies (Olowofela et al., 2019). Also, a radiometric method has been used to determine the level of exposure of miners to natural radiation, inhabitants around a cement factory to radiation, farmers to natural radiation, borehole drillers to radiation hazards, inhabitants around mining sites to radiation and dwellers around a dumpsite to natural radiation (Adagunodo et al., 2021, 2018; Omeje et al., 2019; Usikalu et al., 2019; Usikalu, Oderinde, Adagunodo, Akinpelu et al., 2018a).

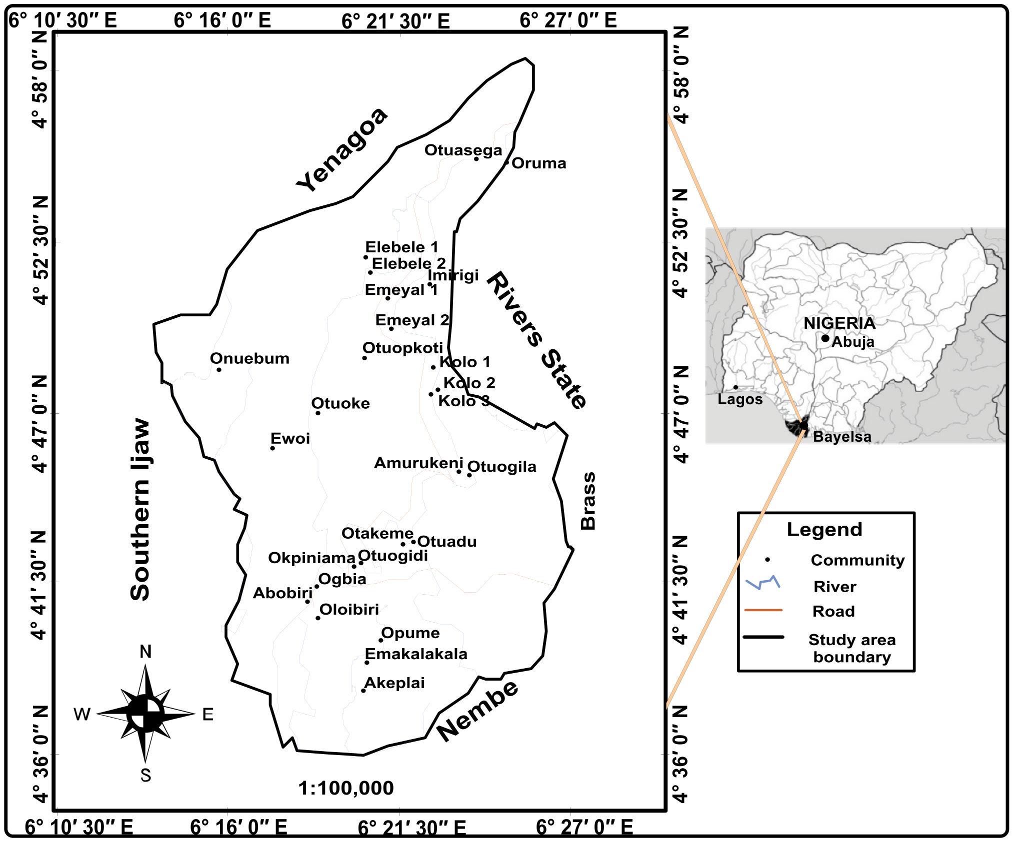
As it is important to carry out geophysical surveys prior to excavation and construction works (Aka et al., 2018; Azahar et al., 2018; Khalil & Hanafy, 2008; Kiernan et al., 2021; Laletsang et al., 2007; Lech et al., 2020; K. Rezaei et al., 2013), so it is also imperative to assess the safety of inhabitants dwelling in an environment (Alazemi et al., 2016; Joel et al., 2019a, 2021; Kaniu et al., 2018; Tzortzis & Tsertos, 2004). The outcome of this study shall reveal the suitability of the area of interest for development of enhanced civil engineering purposes and determination of potential hazardous zones as a result of elevated concentrations of radioelements. This is the major gap that the current study seeks to fill, which is in line with the Sustainable Development Goal (SDG) 11. The SDG 11 projects availability of sustainable cities and communities to all humans by year 2030 (SDG (Sustainable Development Goals), 2019). Some locations were reported as being safe for civil engineering activities in Nigeria (Aka et al., 2018; Joel et al., 2019b; Oladejo et al., 2020; Olayanju et al., 2017) which were declared as unsafe for inhabitants from the radiometric survey (Amana et al., 2021; Ameloko et al., 2019; Joel et al., 2021; Oladapo et al., 2022; Omosehinmi & Arogunjo, 2016; Usikalu et al., 2019). This type of anomaly is not only peculiar to Nigeria, it had been experienced in some other parts of the world (Asif et al., 2016; S. Rezaei et al., 2019; Shahbazi-Gahrouel, 2003; Shehzad et al., 2019) as a result of the heterogeneous nature of near-surface layers. The following few studies had recently combined geophysical/geotechnical data with radiometric data to assess the soil foundation's characteristics and environmental impact assessment for suitability of safe urban extension (Omar et al., 2021; Saad et al., 2020; Sakr et al., 2021, 2022). The aim of this study is to integrate uphole seismic refraction and radiometric methods to determine the foundation bed characteristics and environmental safety of inhabitants in part of Bayelsa state against radiation exposure for an enhanced subsurface integrity check.

1.1. The location and geological settings of the study area

The current location under investigation lies within the coastline of Bayelsa State, south–south Nigeria (Figure 1). There are 32 autonomous communities in the study area with Ogbia being her administrative headquarters. There are traverses of several major and minor roads and networks of hydrocarbon pipelines that are connected to flow stations and tie points in the study area. It has an approximate area of 100 km^2. The topography of the area of study is low lying with a varying elevation of up to 20 m above the mean sea level around the inland with an elevation less than that towards the southwestern zone of the study area. The study area is drained by creeks and tributaries that are linked to River Nun (Brisibe & Pepple, 2018; Oyinkuro & Rowland, 2017). Up to 80% of the area of study is being occupied by water with the landmass covering from Epebu to Amakalakala. Several creeks are noticeable towards the southern part of the study area that extends into the Atlantic Ocean through Brass and Akassa towns. Thickets with arable land are found in the northern part of the study area, while a mangrove exists on the lower delta of the same region (Jim-Ogbolo, 2011). Throughout the year, heavy rainfall is experienced across the land. Like every other part of Nigeria, the climate of Ogbia local government is characterised by a bimodal regime. The rainy season starts from mid-March to mid-November with sporadic downpours usually experienced during the dry season, especially at the end of January to mid-February.

The Nigerian geological domains are encapsulated within the reformed West African basement rocks (Adagunodo et al., 2018). In Nigeria, the most pronouncing geological settings are the basement rocks and sedimentary Basins (Oladejo et al., 2020; Sunmonu et al., 2012). Ogbia and its environs is an integral of the Niger Delta Basin (Figure 2). The Niger Delta's depositional

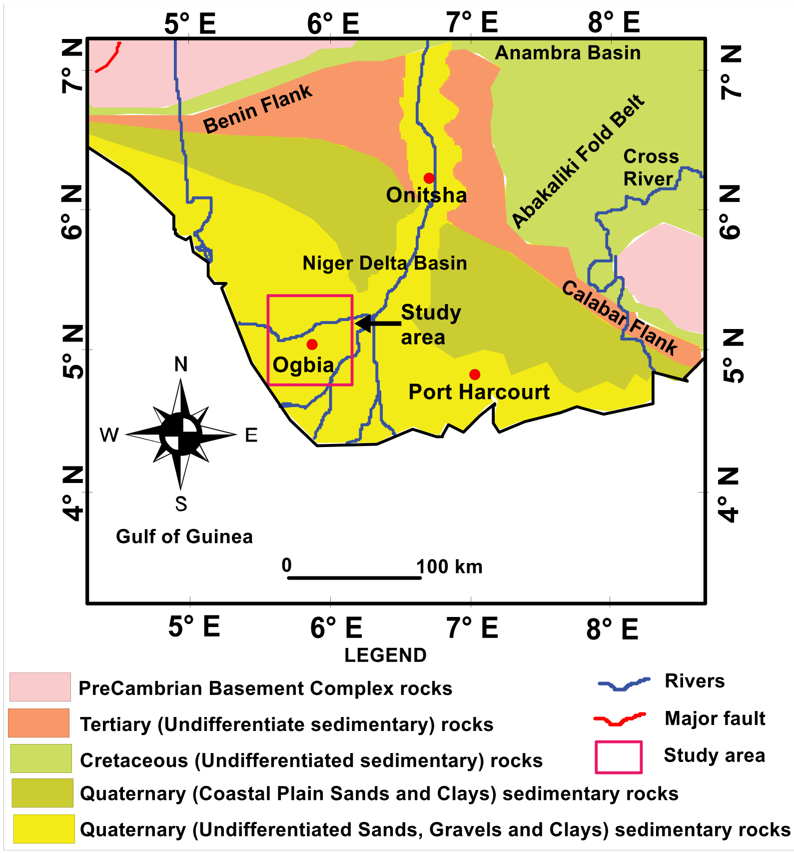
Figure 1. Location map of the study area.



history had been traced back to the Paleocene era (Adeoti et al., 2013; Doust & Omatsola, 1989). Akata, Agbada and Benin Formations are the basic lithostratigraphic units in the Niger Delta (Bayowa et al., 2021, 2019b). The deepest of the three formations is Akata Formation and it is majorly composed of shale with some intercalations of some silty and sandy beds. Akata Formation is believed to be the major hydrocarbon window known as the source rock in the Niger Delta. This formation has a thickness of approximately 7,000 m with age varying from Eocene to Recent (Doust & Omatsola, 1990). The next formation above Akata is the Agbada Formation that is the chamber that stores hydrocarbon for exploration and production in the Niger Delta. It is composed of alternating shales and sandstones. The shales are the cap rocks or seals while the sandstones are the reservoirs in this formation. Some of the minerals present within the sandstones in this formation include elite, kaolinite, quartz, glauconitic, calcareous and potash feldspar. Its thickness is about 3,700 m, with age varying from Miocene to Pliocene (Evamy et al., 1978). The youngest or shallowest of these strata is the Benin Formation that is composed of the alluvial deposits and continental sands. The Benin Formation is chiefly composed of highly porous sandstones that are massive enough to house freshwater. Its thickness is about 2,000 m with age varying from Miocene to Recent (Avbovbo, 1978; Weber & Daukoru, 1975). The lithostratigraphic columns of these three units are shown in Figure 3.

Overlying these three formations are various quaternary deposits which are of Tertiary in age (Oyinkuro & Rowland, 2017). The quaternary sediments are majorly composed of undifferentiated sands, gravels and clays (Figure 2). Sands and gravels are geotechnically fit for civil engineering beds, while clays are threats to structure's integrity, especially when the structure's foundation is laid on thick clay (Adewoyin et al., 2021; Elgohary et al., 2022; Okeniyi et al., 2022; Soupios et al., 2007).

Figure 2. Geological map of Niger Delta showing the study area. Source: (NGSA (Nigeria Geological Survey Agency) (2022).



2. Materials and methods

2.1. Data acquisition and data processing for uphole seismic refraction

For the design of the uphole survey, a hydrophone with a 5 kg cylindrical body were fastened to a marine rope and lowered into the hole (Figure 4). The essence of the cylindrical weight is to ensure that the hydrophone is placed uprightly and floats inside the borehole, stability is increased in the trough-spread as the spread hits the basement of the borehole (Adeoti et al., 2013). The hydrophone used required that the drilled hole be fluid-filled (Opara et al., 2017). The rope was pre-calibrated and logged up to a seismograph (seistronix RAS-24). The configuration of the borehole depths used in this study were 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 12.5, 15.0, 17.5, 20.0, 22.5, 25.0, 27.5, 30.0, 32.5, 35.0, 37.5, 40.0, 42.5, 45.0, 50.0, 55.0 and 60.0 m. These upholes were acquired along well-established seismic lines.

For an individual uphole point, a rotary method at an intersection between the source and the receiver lines was used for each drilled hole and flushed uninterruptedly for 20 minutes. This is to ensure that the drilled hole is stable for an effective and smooth installation of the plastic casing. An array of 32 hydrophones that were placed at different points for the acquisition of 37 uphole data were let down into a drilled shallow hole of about 60 m deep. In logging the boreholes, the energy source point was located at an offset of 2 m away from the uphole point. The energy source point hole was then drilled to about 2 m depth. A group of 5 primed caps (detonators) were then buried in the energy source point and triggered through a blaster. The detonator was shot at varying depth intervals from 0.5 to 60.0 m. The difference in the shot of the detonator was to ensure that the source and the receiver were not at the same datum. This arrangement would enable the first breaks and other noticeable signals with less time arrival time (delayed events) to be identified (Adeoti et al., 2013). After the initial setup of seistronix RAS-24 (the recording

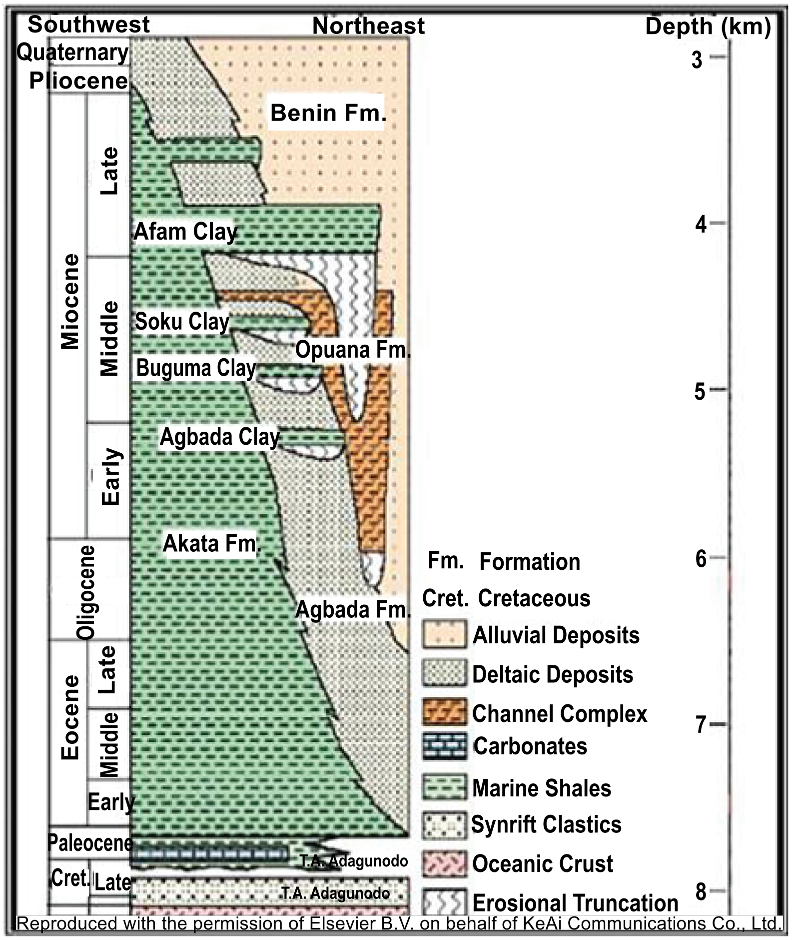


Figure 3. The lithostratigraphic units in the Niger Delta. Source: Bayowa et al. (2021).

equipment) and safety procedure considerations for an uphole survey, the firing command was sent from the trigger unit, which provided the required voltage discharge needed to trigger the explosives. Before the blasting (of the energy source), the trigger unit was connected to the seismograph for the recording of the traces.

A digital seismic waveform processing software known as Ixseg2segy (Interpex Limited, 2015) was used to process the seismic data that was recorded by seistronix RAS-24. This software is installed on a laptop to enable the mobility of the workstation used in this study. The first breaks as revealed in Figure 5 were identified from the traces. The velocities of the first and second layers were filtered through the velocity model function on the Ixseg2segy. All the travel times were filtered to take into cognisance the 2 m offset between the source and the borehole head. The travel time filtering is to correct the offset error and approximate the recorded data as if the source and the borehole head were placed at the same point using Equation 1 (Opara et al., 2017). For each point, a travel time versus (source-receiver) distance graph was plotted to obtain the thicknesses and velocities of the available strata (Figures 6(a-d)). The inverse of the slope of the first layer was used to generate the velocity of the weathered layer while the inverse of the second layer's slope resulted in the velocity of the consolidated layer (Opara et al., 2017). The intersection between the two slopes was used to estimate the thickness of the unconsolidated layer (depth to refractor) (Adeoti et al., 2013). Similarly, the depth to refractor can be estimated by Equation 2. The lithologic characterisation based on the grain sizes of the sediments in each stratum was done following the ASTM (American Society for Testing and Materials (1990) standard. This standard is presented in Table 1.

Figure 4. A set-up of an uphole seismic refraction survey in the study area.

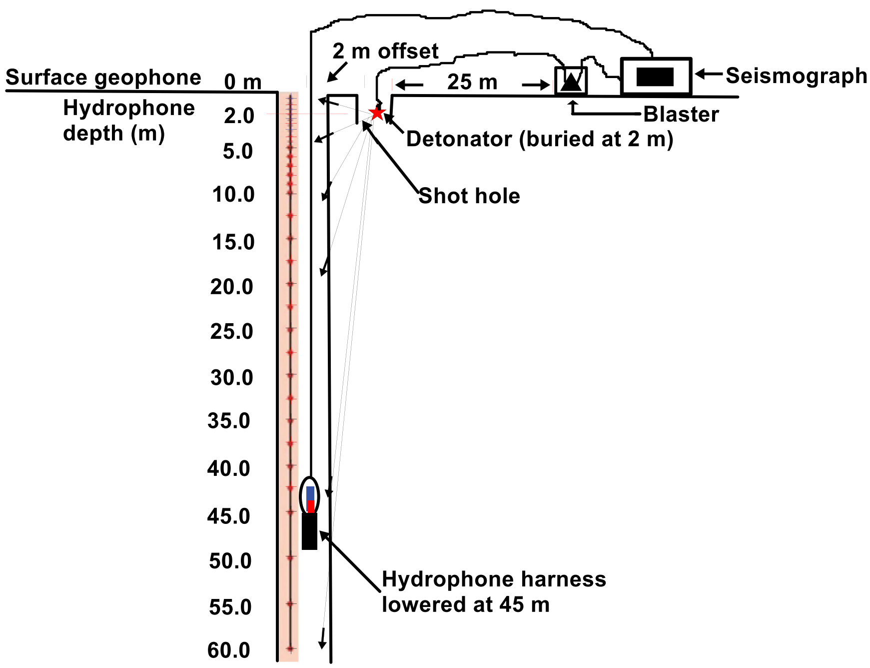
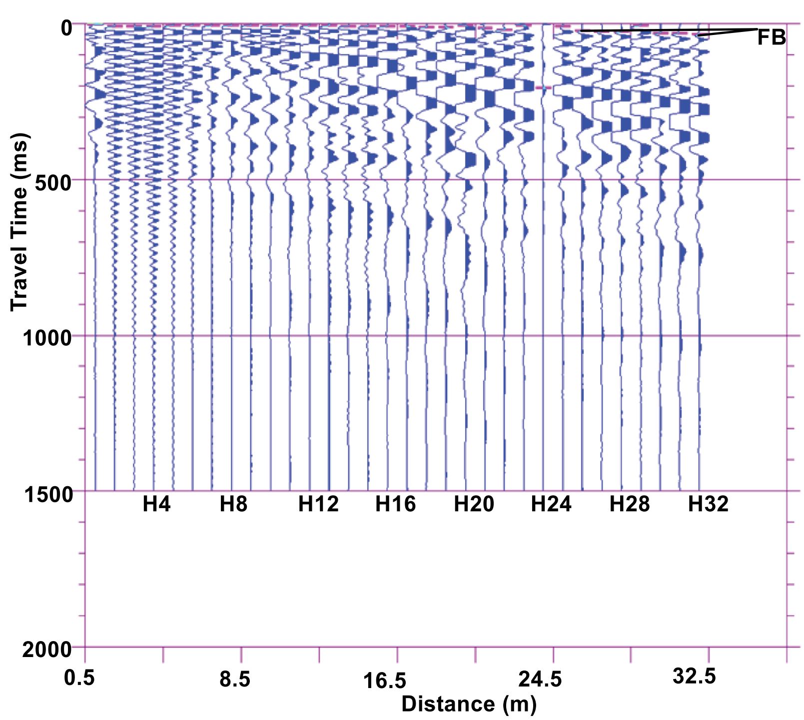


Figure 5. A representation of the seismic trace revealing first breaks (FB) and hydrophone locations (H).



$$t^* = t \times \frac{h^*}{\sqrt{(h^*)^2 + (x^*)^2}} - t_0 \quad (1)$$

where t_0 is the offset-corrected time at zero receiver's depth, t is the one-way time being measured, t^* is the vertical time being corrected, h^* is the subtraction of source depth from the receiver depth and x^* is the offset length (distance from the source to the borehole head).

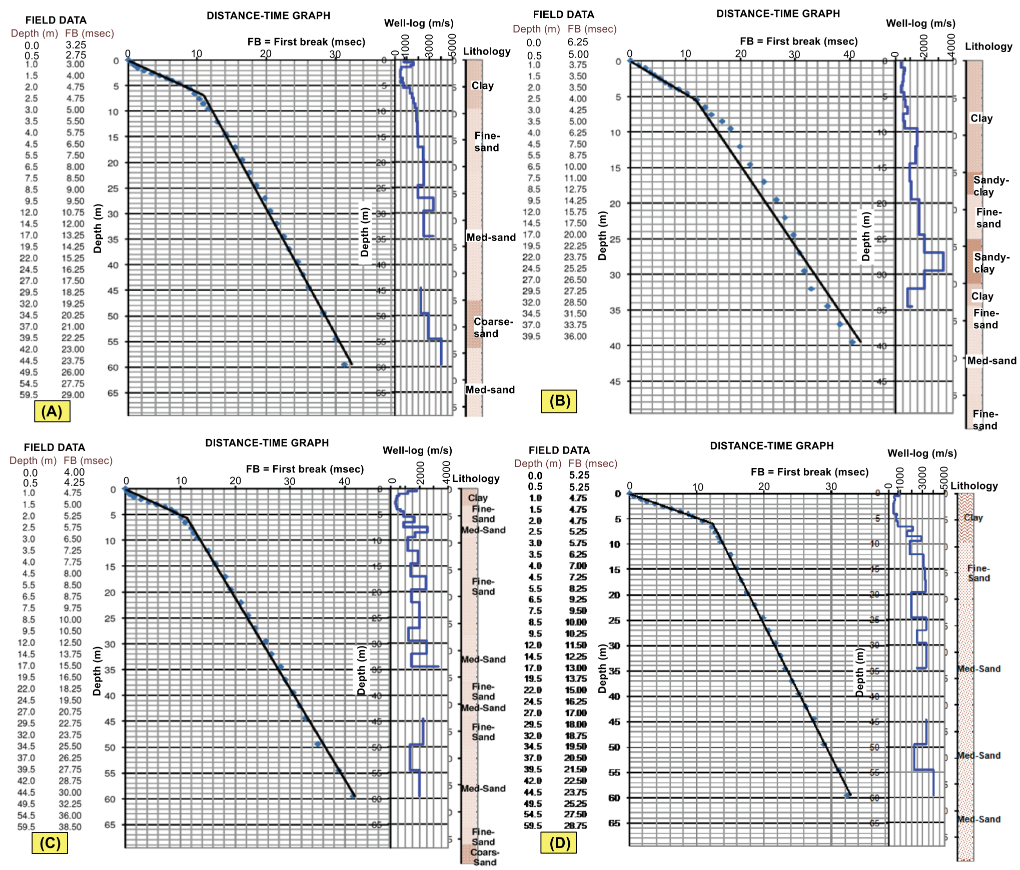


Figure 6. Uphole seismic refraction field data, distance-time graphs, well-logs and litho-logs of some selected stations. (a) Station 02. (b) Station 07. (c) Station 09. (d) Station 12.

Table 1. Lithologic characterisation by grain sizes. Source: **ASTM (American Society for Testing and Materials (1990)**

Grain diameter	Sediment	Particle	Rock type
Above 11.8	Gravel	Boulder	Conglomerate (rounded)
2.5–11.8	Gravel	Cobble	Breccia (angular)
0.08–2.5	Gravel	Pebble	-
0.002–0.08	Sand	Sand	Sandstone
0.0002–0.002	Mud	Silt	Siltstone
Below 0.0002	Mud	Clay	Claystone, Mudstone, Shale

$$H = \frac{(t_i) \times (V_a) \times (V_b)}{2\left((V_b)^2 - (V_a)^2\right)^{\frac{1}{2}}} \tag{2}$$

where H is the depth to refractor, t_i is the intercept of the refracted arrival time, V_a is the velocity of the unconsolidated layer and V_b is the velocity of the consolidated layer.

2.2. Data acquisition and data processing for radiometric method

The in-situ measurements of ^{238}U, ^{232}Th, ^{40}K and gamma dose rates were obtained from the 37 points that were used for the uphole survey using a portable gamma spectrometer known as Super-Spec (RS—125). This geophysical field equipment is known for its field ruggedness and its easy operation mode. It is useful to determine and assess the background radiation of an environment. The accuracy of this spectrometer, which was manufactured by the Canadian Geophysical Institute, is about 95% (Adagunodo et al., 2018). The spectrometer has an in-built detector, high sensitivity, data storage ability and direct assay readout (Orosun et al., 2020a). The assay mode of the spectrometer enables sample concentration analysis and direct display of data from the screen, that is, the values of ^{238}U in ppm, ^{232}Th in ppm, ^{40}K in % and dose rate in nGyh^{-1} (Usikalu et al., 2020).

Before the measurements of ^{238}U, ^{232}Th, ^{40}K and gamma dose rate at each location, the gamma spectrometer will be switched on and held for a five-minute waiting time to ensure that the equipment is auto-stabilized with the natural radioelements in the environment. The measurements at each spot were taken by setting the spectrometer to assay mode with a full sampling count of 120 seconds per assay (Radiation Solution Inc, 2015). To ensure accuracy, the background radiation readings of ^{238}U, ^{232}Th, ^{40}K and dose rate were taken at assay mode five times at each location. The activity concentrations of radioelements that were recorded from the spectrometer were converted to Becquerel per kilogram (Bqkg^{-1}) by using the standard conversion factor of Doust and Omatsola (1989) and (IAEA (International Atomic Energy Agency), 2003). The mean and standard deviation of 5-point measurements at each location was estimated and recorded on a geophysical field sheet. The three radioelements and estimated dose rates in the study area are presented as maps. An in-situ survey was chosen over an ex-situ approach because it is fast and cost-effective with regard to the data points that will be acquired at the end of the survey (Orosun et al., 2020b).

The absorbed dose rate (DR) denotes the radiological dose being received from an open-air at a meter higher above the crust. This dose is a function of the three basic radioelements emanating from the subsurface to the environment. As supported by previous publications (Adagunodo et al., 2018; Usikalu et al., 2020), a high correlation had been known between the field DR and the estimated DR. In view of this, the field DR was used to generate the spatial map, while the estimated DR was used for further safety assessment calculations. The DR is estimated by using Equation (3) as given by UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (2000).

$$\mathrm{DR}\ \left(\mathrm{nGyh}^{-1}\right) = 0.436\mathrm{AC_U} + 0.599\mathrm{AC_{Th}} + 0.0417\mathrm{AC_K} \tag{3}$$

where AC_U, AC_{Th} and AC_K are the activity concentrations of ^{238}U, ^{232}Th and ^{40}K, respectively.

The annual effective dose equivalent (AEDE) denotes the sum of radiological effective doses that one receives in a year. The effective doses are determined for both outdoor (environmental exposure) and indoor (in case the soils in Ogbia are used as parts of building materials) based on Equations (4) and (5) as given by UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (2000).

$$\mathrm{AEDE_{Outdoor}}\ \left(\mathrm{mSvy}^{-1}\right) = 24\mathrm{hours} \times 365\mathrm{days} \times 0.7\ \mathrm{SvGy}^{-1} \times 10^{-6} \times 0.2 \tag{4}$$

$$\mathrm{AEDE_{Indoor}}\ \left(\mathrm{mSvy}^{-1}\right) = 24\mathrm{hours} \times 365\mathrm{days} \times 0.7\ \mathrm{SvGy}^{-1} \times 10^{-6} \times 0.8 \tag{5}$$

Factors 0.2 and 0.8 in Equations (4) and (5) signify a 20% outdoor occupancy factor for the inhabitants and an 80% indoor occupancy factor for the dwellers living in the houses that were built using the terrain soils for 24 hours a year.

A dose received by organs (that is gonad), bone marrow and cells of the bone in a year, which is known as the annual gonadal equivalent dose (AGED) is estimated by using Equation (6) as given by UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (1988) and Orosun et al. (2019).

$$\mathrm{AGED}\ \left(\mu \mathrm{Svy}^{-1}\right) = 3.09\mathrm{AC_U} + 4.18\mathrm{AC_{Th}} + 0.314\mathrm{AC_K} \tag{6}$$

The internal hazard index (H_{In}) and the external hazard index (H_{Ex}) are estimated by using Equations (7) and (8) as given by EC (European Commission) (1999) and Usikalu et al. (2020). These indices are used to measure the risks to respiratory organs when exposed to radon and its remaining short-lived daughters.

$$H_{In} = \frac{AC_U}{185} + \frac{AC_{Th}}{259} + \frac{AC_K}{4810} \tag{7}$$

$$H_{Ex} = \frac{AC_U}{370} + \frac{AC_{Th}}{259} + \frac{AC_K}{4810} \tag{8}$$

The gamma radiation index ($I_{\gamma r}$) denotes one of the parameters used to assess the level of human safety when exposed to gamma-radiation. It is estimated by using Equation (9) as given by EC (European Commission) (1999), UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (2000), and Orosun et al. (2020b).

$$I_{\gamma r} = \frac{AC_U}{150} + \frac{AC_{Th}}{100} + \frac{AC_K}{1500} \tag{9}$$

The alpha radiation index ($I_{\alpha r}$) denotes the assessment of human safety when exposed to alpha radiation as a result of radon gas and its short-lived daughters. This is estimated by using Equation (10) as adopted by Raghu et al. (2017).

$$I_{\alpha r} = \frac{AC_U}{200} \tag{10}$$

The radiation equivalent (Ra_{eq}) denotes a single index used to evaluate the gamma radiation level of exposure when the inhomogenous activity concentrations of ^{238}U, ^{232}Th and ^{40}K are mixed. It is estimated by using Equation (11) as adopted by Adagunodo et al. (2018).

$$Ra_{eq} = AC_U + 1.43AC_{Th} + 0.077AC_K \tag{11}$$

The activity utilization index (AUI) is used to assess the DR in the air from different combinations of the basic within a building. The buildings protect human beings from outdoor radiation and could also act as a source of radiation (UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 2000). It is imperative to estimate the AUI to be certain that the soils are safe to be used as building materials in the study area. If the radiation emitted by outdoor sources is high, the walls of buildings could absorb this type of radiation. Consequently, the absorbed radiation will lead to an increase of an indoor DR in the air. The AUI is estimated based on Equation (12) as adopted by Ravisankar et al. (2016).

$$AUI = \left(\frac{AC_U}{50}\right) f_U + \left(\frac{AC_{Th}}{50}\right) f_{Th} + \left(\frac{AC_K}{500}\right) f_K \tag{12}$$

where f_U, f_{Th} and f_K are the fractional contributions of ^{238}U, ^{232}Th and ^{40}K to the total indoor DR in air. To ensure that the soils are safe for the construction of a well-befitting house, an index of unity is used for f_U, f_{Th} and f_K, respectively.

The excess lifetime cancer risk (ELCR) denotes the index that assesses whether a man is free from carcinogenic diseases when he is being exposed constantly for a long time to radionuclides from environmental media. The ELCR is estimated by using Equation (13) as adopted by UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (2000)

where 70 denotes the life expectancy of 70 years and 0.05 is the risk factor in Sv^{-1}, for the public being exposed to a cancer-causing environment.

$$ELCR = AEDE_{Outdoor} \times 70 \times 0.05 \tag{13}$$

2.3. Geostatistical interpolation of uphole seismic refraction and radiometric data

Kriging was used to interpolate the data in this study. Kriging, also known as Gaussian process regression, is a method of interpolation based on the Gaussian process which is governed by prior covariances. It is a geostatistical gridding technique in numerical analysis that has proven useful in other fields (Adagunodo et al., 2018; Omosehinmi & Arogunjo, 2016; Wang et al., 2008). Kriging produces the most appealing linear unbiased prediction (and visual maps) at unsampled locations (Surfer, 2021). It could be used to measure the spatial correlation between two points. Also, it provides a measure of error or uncertainty of the estimated surface (Wu & Hung, 2016). The general kriging method's equation is as follows:

$$Z(x_0) = \sum_{i=1}^{n} T_i Z(x_i) \tag{14}$$

In Equation (14), $Z(x_0)$ denotes the unknown but estimated Z value in x_0 point; $Z(x_i)$ denotes the value of the known samples around the unknown sample points; n is the number of known sample points; T_i is the weight of the i^{th} sample point; $Z(x_0)$ can be estimated by using the number of known sample points (n).

3. Results and discussion

3.1. Layers' parameters and the effect of soil formation on the shot's quality

The major dataset from this study (that is, the time of arrivals and the hydrophone depths (selected field data shown in Figures 6(a-d)) were used to plot the time-depth graph of each location which was further used to generate the velocity models of the unconsolidated and the consolidated layers. The weathered layer plays a vital role in the quantitative evaluation of uphole data (Ofomola, 2011). This layer allows the ray to pass twice which permits the ray path to be determined clearly (Ofomola, 2011; Ogagarue, 2007). The time-depth graphs (which were used to generate the layers' parameters), well-logs and litho-logs of some selected uphole stations are presented in Figures 6(a-d). From these graphs, two segments were presented. The inverse of the gradient of the direct (waves) arrivals (first segment) produced the velocity of the unconsolidated layer (V_a), while the inverse of the gradient of the refracted arrivals produced the velocity of the consolidated layer (V_b) (Opara et al., 2017). The summary of the layers' parameters for the 37 uphole points in the study area is presented in Table 2.

The elevation of the study area varies from 1.0 to 6.0 m with an average of 3.61 m. This shows that the topography of Ogbia and its environs is low and the values conform with the topographic reports from the coastal environment of Nigeria (Adagunodo et al., 2018; Adeoti et al., 2013; Adewoyin et al., 2019). The weathering description of the study area is evaluated using an uphole survey. The results reveal a two-layer model in all the stations. The V_a varies from 411.0 m/s at station 026 to 882.0 m/s at station 020 with the mean of 517.84 m/s. The variations in V_a reveal the inhomogeneity of the weathered layer. It also indicates the possibility of smooth static behaviour in the study area. The H varies from 2.2 m at station 01 to 7.5 m at station 013, with

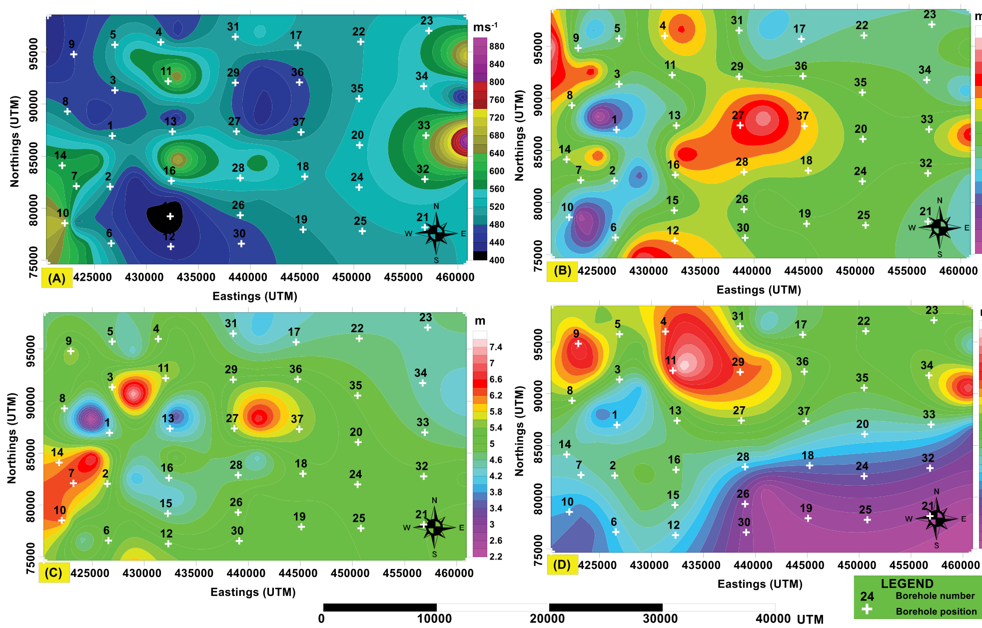
Table 2. Summary of the layers' parameters in the study area

S/N	Elev. (m)	H (m)	V_a (m/s)	V_b (m/s)
01	2.2	2.2	450.0	1035.0
02	3.2	6.9	603.0	2450.0
03	4.8	5.1	468.0	2495.0
04	4.0	4.9	465.0	1576.0
05	4.0	4.7	417.0	2765.0
06	2.1	4.5	580.0	1307.0
07	2.2	5.5	470.0	1135.0
08	4.3	5.4	471.0	2242.0
09	5.3	5.6	459.0	1770.0
010	2.4	6.3	689.0	1703.0
011	3.7	4.3	579.0	1992.0
012	2.8	5.9	465.0	2601.0
013	2.5	7.5	467.0	1735.0
014	2.4	4.3	519.0	1993.0
015	3.2	5.2	432.0	1943.0
016	3.5	4.0	420.0	1431.0
017	2.8	4.1	548.0	1650.0
018	3.1	4.3	581.0	2300.0
019	1.1	5.3	494.0	1944.0
020	2.0	4.6	882.0	2542.0
021	5.5	4.2	413.0	1600.0
022	2.7	4.5	730.0	2115.0
023	4.1	4.7	508.0	1751.0
024	1.6	5.3	535.0	1758.0
025	1.0	4.8	525.0	1757.0
026	3.2	4.2	411.0	1970.0
027	3.7	3.3	436.0	1818.0
028	3.2	5.3	690.0	2511.0
029	6.0	5.5	667.0	2091.0
030	5.1	5.3	452.0	2441.0
031	5.1	4.3	413.0	1866.0
032	5.5	3.3	487.0	1881.0
033	5.5	3.3	422.0	1797.0
034	5.5	4.6	609.0	2129.0
035	5.5	5.0	532.0	1968.0
036	4.6	5.0	441.0	1835.0
037	4.0	6.8	428.0	2695.0
Mean	3.61	4.86	517.84	1961.94

Note. S/N = station number, Elev. = elevation, H = depth to refractor, V_a = velocity of the unconsolidated layer, V_b = velocity of the consolidated layer

a mean of 4.86 m. This result shows that the overburden in the study area is thin. The $V_b$varies from 1035.0 m/s at station 01 to 2765.0 m/s at station 05, with the mean of 1961.94 m/s. An indefinite thickness is present at the consolidated layer. The pattern of the V_b in the study area is adjudged as being competent enough for the acquisition of good seismic reflection data within the Niger Delta Basin (Enikanselu, 2008).

Figure 7. Uphole seismic refraction geospatial maps. (a) Weathered layer's velocity. (b) Consolidated layer's velocity. (c) Overburden thickness. (d) Elevation.



3.2. Foundation bed's characteristics

The geospatial distributions of the weathered layer's velocity, consolidated layer's velocity, overburden thickness and elevation are presented in Figures 7(a-d). The varying degrees of the velocities recorded within the weathered layer revealed the inhomogeneity of this stratum (Figure 7(a)). The entire area of study is divided into low-, medium-, and high-velocity zones. A low-velocity zone varies from 400 to 559 m/s, a medium velocity zone varies from 560 to 739 m/s, while a high-velocity zone ranges from 740 to 900 m/s. As reported by Adikwu et al. (2018), the LVL is known to absorb seismic energies, with varying velocities from 250 to 1000 m/s. It is observed that low-velocity zone dominates more than two-third of the study area, with pockets of medium velocity and high velocity being observed at the eastern and southwestern axes. This low velocity could be a result of the anthropogenic fillings within the unconsolidated layer (REFLEXW guide, 2018) or the geological settings of the study area with a low elevation (Oyinkuro & Rowland, 2017), which is evident in Figure 7(d).

In the consolidated layer, a high seismic velocity (>1000 m/s) that is greater than that of the weathered layer's velocity is observed (Figure 7(b)). Unlike the weathered layer, more than 75% of the consolidated layer is characterized by a seismic velocity that is >1500 m/s. A low velocity below the average value of the consolidated layer is observed at the southwestern part and some minor sections along the northwestern zone of the study area. A very high velocity > 2200 m/s (represented by orange colour) is observed towards the central and some parts of the southwestern and northwestern zones of the study area. The range of the seismic velocity observed within the consolidated layer (1035 to 2765 m/s) signifies that the bedrock is competent for civil engineering activities (Adeoti et al., 2013). The pattern of the velocities of the weathered layer and the consolidated layer in the study area is in agreement with the previous works from other parts of the Niger Delta Basin (Adeoti et al., 2013; Adikwu et al., 2018; Ofomola, 2011; Opara et al., 2017; Uko et al., 2016).

The pattern of the overburden thickness in the study area is revealed in Figure 7(c). An uphole technique has been known for the direct measurements of the overburden thickness (Alaminiokuma, 2020). A fairly uniform thickness, which varies from 4.6 to 5.6 m, dominates the study area. From the southwestern flank and some points around the northwestern axis, an overburden thickness > 5.6 m (which is represented by orange colour) is observed. As classified by Sunmonu et al. (2012), overburden < 15.0 m is considered as thin while the one > 15.0 m is considered as thick. Generally, the overburden in the study area is thin. A thin overburden is considered as being favourable for civil engineering activities (Adeoti et al., 2013).

A very low elevation characterises the southern and southeastern parts of the study area (Figure 7(d)). Variations of the elevation in Ogbia and its environs conform with its geological settings. An elevation < 9.9 m is classified as being low (Adikwu et al., 2018). The result shows that the elevation in the study area varies from 0.8 to 6.2 m which signifies that the study area is characterized by a low elevation.

The experimental shot analysis revealed that all the shots in the current study with drilled depth from 5.0 to 7.0 m are weak, except at a shot point. The only exception with the return of good energy is at depth 2.2 m, which is as a result of thinness of the unconsolidated layer. To determine the quality of shots on the field, the data is retrieved from the seistronix RAS-24 to the workstation for quick access to the field data. Traces with highly attenuated amplitudes (which create flatline wiggles) are classified as weak shots (Kurtulus & Sertcelik, 2010). Therefore, the drilled depth up to 10.0 m falls within the consolidated layer. A few shots appeared fair despite the low elevation of the point at which they were established. At such points, explosives were presumably buried within the consolidated layer, hence the good energy returns. There will be a high degree of good shots where the weathered layer's thickness is low, hence the explosive depth in the study area is established within the consolidated layer. Some of the uphole points showed varying degrees of geologic settings that contributed adversely to the quality of shots. At some points where the explosive depths are within the aquiferous zone, there is a possibility that the explosive is in contact with water. At other points, the explosive depths could fall within a continuous clayey formation, which has been proven to have a compacting effect on the explosive (Enikanselu, 2008), thereby reducing the potency of such explosive in the face of a high sleep time. These two phenomena within the aquiferous zone and clayey formation could be responsible for the record of some weak shots at some points with explosive depths within the consolidated layer.

To determine the time delay for static correction in case a seismic reflection survey will be carried out in the study area, the information obtained from this study is extremely significant. This is because the unconsolidated layer needs to be competent before an analysis of the seismic reflection, for tracking the energy source at a sufficient depth such that the ground roll is minimized, which interferes with seismic reflections. In addition, energy can be maximized to the surface by putting the source underneath the weathered zone. It was inferred from the interpretation that up to the depth of 2.0 m, the subsurface materials are loose, unconsolidated and composed of clayey sand. The layer has high porosity and a high degree of saturation which are the attributes of weak and unstable subsoil. Therefore, it is advisable to excavate the topmost weak and unconsolidated layer before the construction of any civil engineering structures in the study area.

3.3. The lithology logs

The lithology in this study based on the borehole log as classified by ASTM (American Society for Testing and Materials (1990) include clay, fine/medium sand, coarse sand and clayey sand. The summary of the litho-logs is presented in Table 3. Two to nine layers are available in the log formation. The minimum number of layers (2 layers) is present in station 013, while the maximum number of layers (9 layers) is observed in station 022. About 95% of the first lithological sequence is composed of clay. The depth of the first lithology varies from 3.0 to 24.0 m. The comparison between the weathered layer's thicknesses and the litho-logs revealed that the overburden thickness of the study area (2.2 to 7.5 m) is within the first lithological sequence (clay). This comparison further justifies the reason for recording some weak shots within the LVL in the study area. One of the characteristics of clay is that it can shrink during the dry season and swell in the rainy season through the aid of minuscule particles found in clay (Okeniyi et al., 2022). This characteristic may later cause differential settlements that can lead to cracks within the columns of civil engineering structures in the study area. Based on the comparison approach between the LVL's thicknesses and the litho-logs, notable excavation within the weathered layer and the use of appropriate foundation designs for any civil engineering construction is advised.

3.4. Radiometric survey interpretation

The geospatial distributions of ^{238}U, ^{232}Th, ^{40}K and the measured DR are revealed in Figures 8(a-d). The activity concentrations of these radionuclides and their measured DR range from 11.0 to 41.0 $Bqkg^{-1}$for ^{238}U, 30.0 to 61.0 $Bqkg^{-1}$ for ^{232}Th, 20.0 to 250.0 $Bqkg^{-1}$ for ^{40}K and 30.0 to 52.0 $nGyh^{-1}$ for measured DR. The estimated mean values for ^{238}U, ^{232}Th, ^{40}K and DR are 24.17 $Bqkg^{-1}$, 43.35 $Bqkg^{-1}$, 86.3 $Bqkg^{-1}$ and 40.63 $nGyh^{-1}$. Figure 8(a) showed varying distributions of uranium concentrations in the study area which trends in the NW–SE direction. The southern and southeastern parts (being marked with red) depict relatively higher values than the global mean of 35 $Bqkg^{-1}$ (UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 2000; Adagunodo et al., 2021). Pockets of troughs with lower values than the global mean are present at the central part of the study area (Figure 8(a)). The distribution of ^{232}Th in the study area is higher than the global mean of 30 $Bqkg^{-1}$ as shown in Figure 8(b) (UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 2000; Usikalu et al., 2019). An irregular trending pattern, with elevated values of thorium, is observed at the central and the SE part of the study area (Figure 8(b)). The activity results for ^{40}K revealed that potassium distributions in the study area are a bit lesser than the global mean of 400 $Bqkg^{-1}$ as revealed in Figure 8(c) (Chandrasekaran et al., 2014). The potassium trends in SE-NW directions, with a noticeable depression at the central part of the study area (Figure 8(c)). Figure 8(d) presented the distributions of the measured DR, with an irregular trending pattern in the area of study. It is shown that the DR is less than the global mean of 57 $nGyh^{-1}$ (Adagunodo et al., 2021; Usikalu et al., 2020). An upshoot trending from the central to the SE region and a trough towards the northern part are observed in the study area (Figure 8(d)).

The wide variations in the compositions of these radioelements show that the study area is composed of series of lithological formations from depositional sediments and rock types (Akpan et al., 2016). The results showed that the background radiation in Ogbia and its environs contain partly ^{238}U-enriched and highly ^{232}Th-enriched soils across the surveyed region. As stated in the World Nuclear Association online library (WNA (World Nuclear Association), 2020), thorium is highly present in nature than uranium. It is fertile rather than being easily split. This characteristic has enabled thorium to be used as fuel together with recycled plutonium (a fossil material) in nuclear reactors. Thorium is a slightly radioactive metal that is naturally present in the subsurface. In some formations, thorium is found in small amounts while its abundance in other formations is about 300% than uranium. Thorium is insoluble when compared to uranium. This justifies why thorium is abundantly available in sands than uranium (WNA (World Nuclear Association), 2020). The transported thorium enriched materials and sediments during the deposition history of the Niger Delta could have been responsible for an elevated concentration of thorium in the study area which is higher than the global mean by a factor of 1.45.

By converting ppm and % of radionuclides to $Bqkg^{-1}$, Beamish and White (2011) showed from airborne radiometric data over Isle of Wight that the abundance of ^{238}U, ^{232}Th and ^{40}K in the crust varied from 11.12 to 40.76 $Bqkg^{-1}$, 14.21 to 59.68 $Bqkg^{-1}$ and 31.3 to 250.4 $Bqkg^{-1}$, respectively. The ranges of radionuclide results from the present study corroborate with that of an Isle of Wight, which was acquired from different sedimentary environments. From the literature, high concentrations of ^{232}Th and ^{238}U are associated with granites and rocks with granitic compositions (Omeje et al., 2019) but sedimentary terrains with intercalations of sands, shales and sandstones are exceptional (Adagunodo et al., 2018; Ogunsanwo et al., 2019; Osae et al., 2006). Therefore, contributions from the lithological sequences to the level of background radiation in the study area are of high importance. Further, inhalation or ingestion of thorium has been linked to death or cancers of internal organs, related diseases in the bloodstream, liver damages, exposure to radon isotopes and damages to the body systems or death (Xing-an et al., 2014). In furthermore, the

Table 3. Summary of the lithology logs

Station No.	Soil formation
01	0–3 m (clay), 3–6 m (fine sand), 6–9 m (clay/fine sand), 9–45 m (fine sand), 45–60 m (fine/coarse sand)
02	0–9 m (clay), 9–45 m (fine sand), 45–60 m (coarse sand)
03	0–15 m (clay), 15–45 m (fine sand), 45–60 m (fine/coarse sand)
04	0–15 m (Clay),15–36 m (fine sand), 36–51 m (fine/coarse sand), 51–60 m (coarse sand)
05	0–15 m (clay),15–36 m (clayey sand), 36–54 m (fine/coarse sand) 51–60 m (coarse sand)
06	0–15 m (clay),15–33 m (clayey sand),30–51 m (fine sand), 51–60 m (coarse sand)
07	0–15 m (clay) 15–45 m (fine sand), 45–60 m (fine/coarse sand)
08	0–6 m (clay), 6–42 m (fine sand), 42–60 m (fine/coarse sand)
09	0–3 m (clay), 3–45 m (fine sand), 45–60 m (fine/coarse sand)
010	0–9 m (clay), 9–48 m (fine sand), 45–60 m (coarse sand)
011	0–9 m (clay), 9–36 m(fine sand), 36–60 m (fine/coarse sand)
012	0–9 m (clay), 9–33 m (fine sand), 33–60 m (fine/coarse sand)
013	0–15 m (clay), 15–60 m (fine/coarse sand)
014	0–9 m (clay),9–42 m (fine sand), 42–60 m (fine/coarse sand)
015	0–9 m (clay), 9–24 m (fine sand), 24–51 m (fine/coarse sand), 51–57 m (fine sand), 57–60 m(coarse sand)
016	0–9 m (fine sand), 9–48 m (fine/coarse sand), 48–60 m (fine sand)
017	0–15 m (clay), 15–45 m (fine sand), 45–60 m (fine/coarse sand)
018	0–15 m (clay), 15–42 m (fine sand), 45–57 m (fine/coarse sand), 57–60 m (coarse sand)
019	0–9 m (clay), 9–27 m (clayey sand), 27–51 m (fine sand), 51–54 m (fine/coarse sand), 54–60 m (coarse sand)
020	0–24 m (clay), 24–27 m (clayey sand), 27–42 m (coarse sand), 42–60 m (fine/coarse sand)
021	0–15 m (clayey sand), 15–39 m (coarse sand) 39–60 m (clay/coarse sand)
022	0–18 m (clay), 18–21 m (clayey sand), 21–24 m (fine sand), 24–27 m (coarse sand), 27–30 m(coarse sand), 30–37 m (fine/coarse sand), 37–45 m (coarse sand), 45–51 m (fine/coarse sand), 51–60 m (coarse sand)
023	0–18 m (clay), 18–27 m (clayey sand), 27–30 m (coarse sand), 30–37 m (fine/coarse sand), 37–42 m (coarse sand), 42–51 m (fine/coarse sand), 51–60 m (coarse sand)
024	0–15 m (clay), 15–27 m (clayey sand), 27–33 m (fine sand), 33–48 m (coarse sand), 48–54 m (fine/coarse sand), 54–60 m (coarse sand)

(*Continued*)

Table 3. (*Continued*)

Station No.	Soil formation
025	0–6 m (clay), 6–18 m (fine sand), 18–24 m (clayey sand), 24–37 m (fine sand), 37–42 m (coarsesand), 42–54 m (fine sand), 54–60 m (coarse sand)
026	0–9 m (clay), 6–54 m (fine sand), 54–60 m (coarse sand)
027	0–3 m (clay), 3–15 m (fine sand), 15–60 m (fine/coarse sand)
028	0–9 m (clay), 9–24 m (fine sand), 21–60 m (fine sand)
029	0–3 m (clay), 3–6 m (clayey sand), 6–15 m (fine sand), 15–18 m (clay), 18–24 m (fine sand), 24–54 m (clayey sand), 54–60 m (fine sand)
030	0–9 m (clay), 9–18 m (fine sand), 18–60 m (fine/coarse sand)
031	0–9 m (clay), 9–24 m (fine sand), 24–60 m (fine/coarse sand)
032	0–15 m (clay), 15–27 m (clayey sand), 27–42 m (coarse sand), 42–60 m (fine/coarse sand)
033	0–15 m (clay), 15–30 m (clayey sand), 30–60 m (fine/coarse sand)
034	0–15 m (clay), 15–33 m (fine sand), 33–60 m (fine/coarse sand)
035	0–15 m (clay), 15–54 m (fine sand), 54–60 m (fine/coarse sand)
036	0–15 m (clay), 15–45 m (fine sand), 45–60 m (fine/coarse sand)
037	0–15 m (clay), 15–42 m (fine sand), 42–57 m (fine/coarse sand), 57–60 m (coarse sand)

pronounced chemical effect that has been linked to exposure to uranium is kidney toxicity (DUF6 Guide (Depleted Uranium Hexafluoride), 2001).

3.5. Surface radioelements ratios

Estimation of radioelements ratios is used to map subtle radioelements concerning geological and environmental studies (Minty, 2011). Radioelements ratios are also used to eliminate the effect of non-radioactive regolith in the radiometric survey. This is achieved since the gamma-rays attenuation coefficients used to determine uranium, thorium and potassium are similar to the ones encountered by air within the range of earth materials during the acquisition of radiometric data. Ratios between radioelements are often used to determine the radioelement that is being enriched or being depleted. For example, ratios between $^{238}U/^{40}K$ and $^{238}U/^{232}Th$ are essential in the exploration of uranium mobility (Abdrabboh, 2017). When the values of either of the two ratios are greater than unity, it shows that the formation is enriched with uranium (Darnley, 1972). These two ratios are often used in uranium exploration to determine the migration and accumulation of ^{238}U. In another perspective, Boyle (1982) reported that the ratios between radioelements (especially $^{232}Th/^{40}K$ and $^{238}U/^{40}K$) are used to minimize the effect of the geometry of the terrain on the concentrations of radionuclides in such environment. Another key ratio to determine the enrichment ability of thorium is $^{232}Th/^{40}K$. During the hydrothermal alteration events, thorium an immobile element is ascertained not to have migrated with potassium (Abdrabboh, 2017; Minty, 2011). The ratio of thorium to potassium is an essential pointer to identify the potassium-metasomatism alteration zones. As estimated by Galbraith and Saunders (1983), the mean ratio of $^{232}Th/^{40}K$ within the crust is usually equaled 0.0005, a value greater than this shows that the terrain is gradually becoming enriched with that would be hazardous to inhabitants in such an

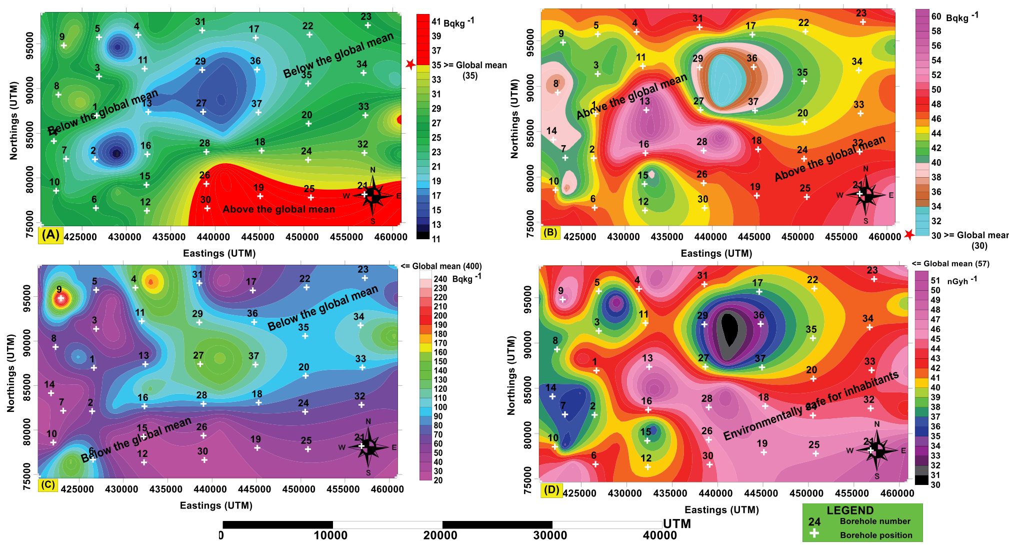


Figure 8. Geospatial maps from radiometric survey. (a) Uranium distributions. (b) Thorium distributions. (c) Potassium distributions. (d) Dose rate distributions.

environment. For environmental impact assessment studies, four ways to determine radioelements ratios are U/K, Th/K, U/Th and Th/U with global means of 0.067, 0.067, 0.260 and 3.500, respectively (UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 1988).

The geospatial radioelements ratios for $^{238}U/^{40}K$, $^{232}Th/^{40}K$, $^{238}U/^{232}Th$ and $^{232}Th/^{238}U$ are shown in Figures 9(a–d). The ratios varied from 0.05 to 1.35 for $^{238}U/^{40}K$, 0.15 to 1.75 for $^{232}Th/^{40}K$, 0.2 to 0.95 for $^{238}U/^{232}Th$ and 1.0 to 5.0 for $^{232}Th/^{238}U$, respectively. The central part in Figure 9(a), which is marked by "X", is the only region with lesser values than the global average of 0.067 for $^{238}U/^{40}K$ (UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 1988). The range of values in Figure 9(b) revealed that the $^{232}Th/^{40}K$ contents in the study area are greater than the global mean of 0.067 (UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 1988). The southwestern parts that are marked by "X" in Figure 9(c) and "Y" in Figure 9(d) are the zones with lesser values than the global mean of 0.26 for $^{238}U/^{232}Th$

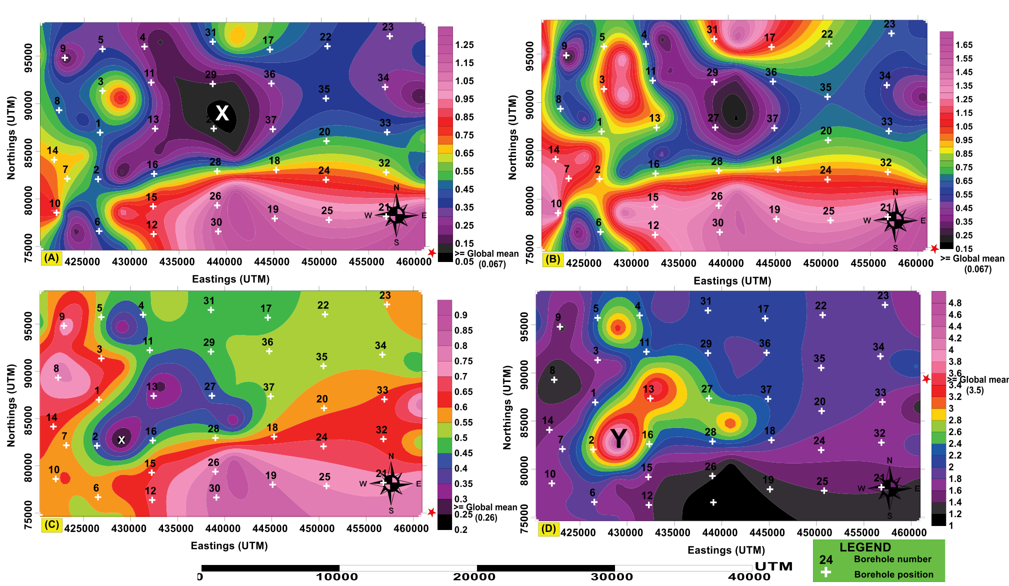


Figure 9. Geospatial maps from radioactivity ratios. (a) $^{238}U/^{40}K$ distributions. (b) $^{232}Th/^{40}K$ distributions. (c) $^{238}U/^{232}Th$ distributions. (d) $^{232}Th/^{238}U$ distributions.

Table 4. Comparison of the radioelement ratios with other studies

Location	$^{238}U/^{40}K$	$^{232}Th/^{40}K$	$^{238}U/^{232}Th$	$^{232}Th/^{238}U$	Reference
Niger Delta, Nigeria	0.05 to 1.35	0.15 to 1.75	0.2 to 0.95	1.0 to 5.0	Present study
Southwestern Nigeria	0.012 to 0.044	0.011 to 0.089	0.497 to 1.086	0.921 to 2.012	Adagunodo et al. (2019)
Tamilnadu, India	0.008 to 0.024	0.052	0.158 to 0.464	2.156 to 6.240	Chandrasekaran et al. (2014)
Northern Pakistan	0.04 to 0.25	0.02 to 0.34	0.34 to 1.83	0.545 to 1.557	Qureshi et al. (2014)
Southeastern Nigeria	0.302 to 0.355	0.227 to 0.584	0.608 to 1.328	0.753 to 1.644	Akpan et al. (2016)
El-Sahu area, Egypt	1.600 to 234.00	2.6 to 49.3	0.1 to 45.5	0.128 to 0.529	Abdrabboh (2017)

and 3.5 for $^{232}Th/^{238}U$, respectively. The geospatial maps of the radioelements ratios showed that 97.3% of $^{238}U/^{232}Th$ contents are less than unity while 97.3% of $^{232}Th/^{238}U$ contents are greater than unity. The ratios of $^{238}U/^{40}K$ showed that 5.4% of the contents are greater than 1. These results (Figures 9(a-d)) suggest that the soils in Ogbia and its environs are enriched with thorium, though a gradual depletion of uranium is noticed from the results as well. In line with Tzortzis and Tsertos (2004), a ratio of $^{232}Th/^{238}U < 1$ is a uranium-enriched terrain while a ratio of $^{232}Th/^{238}U > 1$ is a thorium-enriched terrain. As revealed in Table 4, the trend of results in the present study is in agreement with the outcome of some previous works while a great disparity was noticed in the work of Abdrabboh (2017), which was done in the area of El-Sahu, Egypt. This disparity could have been attributed to the geological formations of the two terrains. The El-Sahu area is an active uranium ore prospecting zone while Ogbia and its environs are overlain with the continental sands and gravel of the Benin Formation. The sedimentary terrain of the El-Sahu area is underlain by younger granite which is exposed at G. Adedia. Above the granites are the lower sandstone, carboniferous limestone and upper sandstone series (Barron, 1907). The carboniferous limestone which is classified as Um Bogma Formation is highly rich in crystalline dolomite, shale, sandstone and ferruginous siltstone (Abdrabboh, 2017). This formation is one of the targets for uranium exploration in Egypt. In line with Olowofela et al. (2019), areas with relatively high values of $^{238}U/^{40}K$ are associated with shale, sandstone and clay. Ramadass et al. (2015) also explained that the concentrations of potassium decreased with an increase in weathering. Based on the previous Section in the geology of the current study, Ogbia and its environs are situated in the sedimentary environment of the Niger Delta Basin. The major three Formations in the Niger Delta are Benin Formation being the youngest, Agbada Formation and (the oldest) Akata Formation. The Benin Formation comprises the Continental Alluvium deposits and upper Coastal Plain Sands that are mainly of sands and gravels (Adagunodo et al., 2017; Doust & Omatsola, 1989). The trend of radioelements ratios results in this study corroborates with the work of Ogunsanwo et al. (2019) whose part of their study covered the Coastal Plain Sands of a sedimentary terrain in Dahomey Basin, Nigeria. In their study, thorium is abundantly available with higher values than the global mean with 25% of the terrain having uranium contents than the global mean while potassium contents are lower than the global mean.

3.6. Environmental safety assessment

The yardsticks to assess the safety of the inhabitants to the radiation exposure in the study area include estimated DR, $AEDE_{Outdoor}$, $AEDE_{Indoor}$, Ra_{eq}, AGED, AUI, H_{In}, H_{Ex}, $I_{\gamma r}$, $I_{\alpha r}$ and ELCR. These parameters are presented in Table 5. The range of the estimated DR varied from 20.28 to 50.47 $nGyh^{-1}$ with a mean of 40.10 $nGyh^{-1}$. The estimated DRs at a height of 1 m in the study area are below the global mean of 57 $nGyh^{-1}$ (Usikalu et al., 2020). The $AEDE_{Outdoor}$ varied from 0.02 to 0.06 $mSvy^{-1}$, with a mean of 0.05 $mSvy^{-1}$. The obtained mean and range for $AEDE_{Outdoor}$ are below the global mean of 0.07 $mSvy^{-1}$ (Adagunodo et al., 2018; Qureshi et al., 2014;

Table 5. Environmental safety assessment in the study area

PT	E. DR (nGy/h)	AEDE out (mSv/y)	AEDE in (mSv/y)	Ra (Bq/kg)	AGED (µSv/y)	AUI	H-in	H-ex	I γ r	I α r	ELCR (× 10^{-3})
ESA 1	43.94	0.05	0.22	101.46	310.29	1.7	0.36	0.27	0.71	0.16	0.19
ESA 2	34.29	0.04	0.17	80.302	241.02	1.28	0.27	0.22	0.56	0.1	0.15
ESA 3	39.7	0.05	0.19	92.297	279.69	1.5	0.32	0.25	0.65	0.13	0.17
ESA 4	44.86	0.06	0.22	103.71	316.66	1.72	0.36	0.28	0.73	0.15	0.19
ESA 5	36.19	0.04	0.18	84.873	254.17	1.33	0.28	0.23	0.59	0.1	0.16
ESA 6	46.53	0.06	0.23	106.49	329.54	1.79	0.36	0.29	0.76	0.13	0.2
ESA 7	33.7	0.04	0.17	78.141	237.69	1.28	0.27	0.21	0.55	0.11	0.14
ESA 8	36.88	0.05	0.18	85.477	260.17	1.42	0.31	0.23	0.6	0.14	0.16
ESA 9	48.47	0.06	0.24	108.79	345.43	1.94	0.38	0.29	0.78	0.15	0.21
ESA 10	40.88	0.05	0.2	95.766	287.25	1.53	0.33	0.26	0.67	0.14	0.18
ESA 11	31.74	0.04	0.16	74.56	222.79	1.15	0.23	0.2	0.52	0.06	0.14
ESA 12	40.86	0.05	0.2	95.126	287.75	1.54	0.32	0.26	0.67	0.12	0.18
ESA 13	38.44	0.05	0.19	89.96	270.28	1.45	0.32	0.24	0.63	0.14	0.17
ESA 14	42.7	0.05	0.21	99.623	300.48	1.58	0.33	0.27	0.7	0.11	0.18
ESA 15	41.95	0.05	0.21	98.236	294.88	1.58	0.35	0.27	0.68	0.15	0.18
ESA 16	40.62	0.05	0.2	94.401	286.15	1.47	0.28	0.25	0.67	0.06	0.17
ESA 17	40.42	0.05	0.2	94.89	283.87	1.49	0.32	0.26	0.66	0.11	0.17
ESA 18	49.05	0.06	0.24	113.51	346.03	1.81	0.36	0.31	0.8	0.09	0.21
ESA 19	47.04	0.06	0.23	109.93	330.93	1.81	0.41	0.3	0.76	0.2	0.2
ESA 20	46.25	0.06	0.23	107.48	325.91	1.78	0.39	0.29	0.75	0.19	0.2
ESA 21	43.89	0.05	0.22	100.39	310.88	1.67	0.33	0.27	0.72	0.1	0.19
ESA 22	38.19	0.05	0.19	88.739	269.08	1.45	0.31	0.24	0.62	0.12	0.16
ESA 23	47.24	0.06	0.23	109.44	333.21	1.8	0.38	0.3	0.77	0.15	0.2
ESA 24	41.05	0.05	0.2	95.632	289.02	1.54	0.32	0.26	0.67	0.12	0.18
ESA 25	49.66	0.06	0.24	116.24	349.17	1.89	0.42	0.31	0.81	0.2	0.21
ESA 26	35.42	0.04	0.17	82.846	249.07	1.34	0.29	0.22	0.58	0.12	0.15
ESA 27	44.63	0.05	0.22	104.48	313.65	1.62	0.33	0.28	0.73	0.08	0.19
ESA 28	50.47	0.06	0.25	116.71	356.2	1.89	0.38	0.32	0.83	0.12	0.22
ESA 29	40.88	0.05	0.2	93.919	289.17	1.56	0.31	0.25	0.67	0.1	0.18
ESA 30	48.57	0.06	0.24	110.65	344.46	1.88	0.37	0.3	0.79	0.13	0.21
ESA 31	20.8	0.03	0.1	47.582	147.33	0.82	0.17	0.13	0.34	0.08	0.09
ESA 32	20.28	0.02	0.1	46.136	143.93	0.83	0.18	0.12	0.32	0.1	0.09
ESA 33	44.37	0.05	0.22	99.21	316.59	1.77	0.34	0.27	0.72	0.13	0.19
ESA 34	26.13	0.03	0.13	60.71	184.16	1.02	0.23	0.16	0.42	0.12	0.11
ESA 35	47.38	0.06	0.23	108.88	335.07	1.77	0.34	0.29	0.78	0.09	0.2
ESA 36	29.64	0.04	0.15	67.99	209.77	1.13	0.23	0.18	0.48	0.08	0.13
ESA 37	30.74	0.04	0.15	69.253	218.82	1.2	0.23	0.19	0.5	0.07	0.13
Mean	**40.10**	**0.05**	**0.20**	**92.81**	**282.99**	**1.52**	**0.32**	**0.25**	**0.65**	**0.12**	**0.17**
Global mean	**57.0**	**0.07**	**0.41**	**370.0**	**300.0**	**2.0**	**1.0**	**1.0**	**1.0**	**0.5**	**0.29**

UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 2000). This shows that the environment poses no risk to the inhabitants. The $AEDE_{Indoor}$ varied from 0.10 to 0.25 $mSvy^{-1}$, with a mean of 0.20 $mSvy^{-1}$. The mean and range obtained for $AEDE_{Outdoor}$ in this study are below the global mean of 0.41 $mSvy^{-1}$ as recommended by UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (2000). This shows that the doses received in a year by the people living in the houses built from the earth materials that were obtained from the study area are safe from gamma radiation exposure. The total AEDE (that is, $AEDE_{Outdoor}$ + $AEDE_{Indoor}$) as estimated by Qureshi et al. (2014) was obtained in this study as 0.48 $mSvy^{-1}$. This value is lower than the global mean of 1 $mSvy^{-1}$ as recommended by ICRP-60 (1990) and 0.52 $mSvy^{-1}$as recommended by UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (2000). The results of the outdoor, indoor and total AEDE showed that the environment of study is safe for the dwellers.

The range of Ra_{eq} in this study varied from 46.14 to 116.71 $Bqkg^{-1}$. This value is lower than the global mean of 370 $Bqkg^{-1}$ (Adagunodo et al., 2021) which corresponds to an external dose of $\leq$ 1.5 mGy^{-1} (Avwiri et al., 2012; UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 2000). The range and mean of values obtained for the Ra_{eq} are within the safe limit. The AGED was estimated to know the effect of background radiation on the sensitive internal organs that could be the target for radiation. These organs include gonads, bone cells, bone surface and bone marrow. The range of AGED in this study varied from 143.93 to 356.20 μSvy^{-1} with a mean of 282.99 μSvy^{-1}. Though the average AGED in this study is not up to the global mean of 300 μSvy^{-1} in an environment and soil (Chandrasekaran et al., 2014), 43% of the total surveyed points are slightly higher than the criterion limit. This result implies that there could be gradual depletion in the amount of the total red blood cells produced by the bone marrow of the inhabitants in the study area (UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 2000; Usikalu et al., 2020). These could result in chronic disease conditions that include anaemia, thalassemia and leukaemia. Of course, all these diseases are the outcome of being overexposed to thorium. The elevated AGED results in the study could have been linked to the contributions of thorium from Equation (6). The AUI estimated in this study varied from 0.82 to 1.94 with a mean of 1.52. The results of AUI showed that whether the soils in the study area are used for building constructions (indoor purposes) or used for outdoor purposes, the environment is safe for a living since the range and mean obtained are below the global limit of 2.0 (Raghu et al., 2017; Ravisankar et al., 2016).

The four indices used to assess the environmental safety in the study area as presented in Table 5 are H_{In}, H_{Ex}, $I_{\gamma r}$ and $I_{\alpha r}$. The H_{In} varied from 0.17 to 0.42, with a mean of 0.32. Meanwhile, the H_{Ex} varied from 0.12 to 0.32, with a mean of 0.25. The results of both H_{In} and H_{Ex} are below the global mean of 1.0 (Adagunodo et al., 2018). These two indices are used to assess the level of exposure of internal organs to radon and its daughters. It implies that the study area is safe from exposure to radon by internal organs. The $I_{\gamma r}$ varied from 0.32 to 0.83 with a mean of 0.65. However the $I_{\alpha r}$ varied from 0.06 to 0.20, with a mean of 0.12. As reported by the European Commission (EC) (1999), excessive gamma radiation $\leq$ 2 corresponds to 0.3 $mSvy^{-1}$. But, UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (2000) warned that dose rates > 1 $mSvy^{-1}$ are hazardous to man. Therefore, to have a safe environment and safe building materials that are free from the emanation of excessive gamma radiation, it is advisable to use an $I_{\gamma r}$ $\leq$ 1 criterion that corresponds to a dose rate of 1 $mSvy^{-1}$ (Ravisankar et al., 2016). In the same study by Ravisankar et al. (2016), $I_{\alpha r}$ $\leq$ 1 corresponds to 200 Bqm^{-3} of indoor radon concentrations. For low concentrations of ^{238}U below 100 $Bqkg^{-1}$, as in the current study, the radon exhalation from the building materials would not be able to produce indoor radon concentrations > 200 Bqm^{-3}. Therefore, a limit of $I_{\alpha r}$ < 0.5 is chosen (Ravisankar et al., 2016). As a result of this, a global mean of 1.0 as recommended by UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation) (2000) is adopted for $I_{\gamma r}$ and a global mean of 0.5 as recommended by Raghu et al. (2017) is adopted for $I_{\alpha r}$. The two indices ($I_{\alpha r}$ and $I_{\gamma r}$) indicate that the inhabitants are safe from gamma and alpha radiations that could emanate from the subsurface either through the indoor pathway or the outdoor pathway.

The ELCR obtained from the area of study varied from 0.09×10^{-3} to 0.22×10^{-3}, with a mean of 0.17×10^{-3}. The range of values and the mean obtained in this study are below the global limit of 0.29×10^{-3} (UNSCEAR (United Nations Scientific Committee on the Effects of Arsenic Radiation), 2000). This result suggests that the inhabitants are safe from having any form of carcinogenic diseases (except for the effect of thorium and AGED that are known to be higher than the global mean in the study area). Furthermore, this result shows that the chance of having cancer by persons residing in the study area for $\geq$ 70 years is low. The result of ELCR in this study is in agreement with the work of Adagunodo et al. (2021) who carried out a radiometric survey in Ijako, Dahomey Basin, Nigeria.

4. Conclusion

This study has been able to successfully integrate a seismic uphole survey and a radiometric survey to determine the foundation bed characteristics and environmental safety of inhabitants in Ogbia and its environs against radiation exposure for an enhanced subsurface integrity check. The use of an uphole seismic refraction survey has proven to be an effective geophysical tool in solving the effect of low velocity within the unconsolidated layer (Gadallah & Fisher, 2009; Hampson & Russell, 1984). Subsurface parameters such as the thickness and the velocity of the unconsolidated layer as well as the velocity of the consolidated layer were determined. The overburden is composed of two-layered earth model heterogenous materials with an average depth of ≈ 5 m. The mean values for the weathered layer's velocity, weathered layer's thickness and consolidated layer's velocity are 517.84 m/s, 4.86 m and 1961.94 m/s, respectively. Clayey materials, which may lead to the high absorption of seismic energy (Kurtulus & Sertcelik, 2010) were observed at the southern part of the study area. The borehole analysis revealed that the study area is composed of alternating sequence of clay and sand.

The radiometric survey revealed that thorium is higher than the global criterion while elevated distributions of uranium than the global limit were noticed at the southern and southeastern parts of the study area. The variation of radioelements in the study area has been attributed to the lithological sequences and depositional history of the Niger Delta. The environmental safety assessments showed that the AGED is slightly higher than the global limit. In view of this, reliance on artificial ventilation (such as air conditioning systems) in the buildings within Ogbia and its environs should not be greater than 50% (Joel et al., 2021).

Though the overburden is thin, it is advisable to excavate the weathered layer (using mini, crawler or backhoe excavators) in order to minimize the effect of clay on the structure's foundations. Furthermore, it is advisable to adopt the appropriate foundation design for the construction of any civil engineering structure in the study area. Periodic environmental assessment is recommended in the area of study to check the rate at which the radioelements are increasing in the subsurface and to proffer a means of remediating the level of increment of the radioelements for the safety of the inhabitants in the study area.

Acknowledgements

The lead author thanks the management of the Covenant University for providing the Solar Powered Light and Electrical Supply System that was used during the data acquisition stage. We appreciate the permission given by the following publishers: NGSA for the production of Figure S2, Elsevier B.V. on behalf of KeAi Communications Co. Ltd to reproduce Figure S3 from Bayowa et al. (2021) and ASTM Standard D-2488-90 to use Table S1 in this study. The effort of all the reviewers of this article is greatly acknowledged. The support from CUCRID is greatly acknowledged.

Funding

The data acquisition of this study was partially supported by the Covenant University's Seed Grant (CUCRID/RC/02.04.21/VC; Covenant University Centre for Research, Innovation and Discovery.

Author details

Theophilus Aanuoluwa Adagunodo[1]
E-mail: taadagunodo@yahoo.com
ORCID ID: http://orcid.org/0000-0001-7810-3323
Oyelowo Gabriel Bayowa[2]

Ayobami Ismaila Ojoawo[3]
Olusegun Oladotun Adewoyin[1]
Patrick Omoregie Isibor[4]
Emmanuel Ayibaifie Jephthah[1]
Nicholas Oliseloke Anie[5]
[1] Department of Physics, Covenant University, Ota, Nigeria.
[2] Department of Earth Sciences, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.
[3] Department of Physics, University of Ibadan, Ibadan, Nigeria.
[4] Department of Biological Sciences, Covenant University, Ota, Nigeria.
[5] Physics Unit, Federal School of Surveying, Oyo, Nigeria.

Disclosure statement
No potential conflict of interest was reported by the author(s).

Availability of data and materials
Data will be made available on a reasonable request.

Citation information
Cite this article as: Investigation of foundation bed's characteristics and environmental safety assessment in some parts of Bayelsa State, south–south Nigeria, Theophilus Aanuoluwa Adagunodo, Oyelowo Gabriel Bayowa, Ayobami Ismaila Ojoawo, Olusegun Oladotun Adewoyin, Patrick Omoregie Isibor, Emmanuel Ayibaifie Jephthah & Nicholas Oliseloke Anie, *Cogent Engineering* (2022), 9: 2119533.

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